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SUPERCONDUCTING MOTORS AND LITHIUM-WATER BATTERIES
FOR TORPEDO PROPULSION*

by

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ABSTRACT5^D

Presently-available information suggests that the performance of the MK 37 torpedo could be improved by the use of a superconducting electric motor powered by a lithium-seawater battery. Details are given and recommendations for future work are described. //

RÉSUMÉ

Les informations présentement disponibles indiquent que le rendement de la torpille MK 37 pourrait être amélioré par un bobinage supraconducteur du moteur électrique et par une pile électrique du type lithium-eau de mer. Quelques détails de ces sources de force motrice sont présentés dans ce rapport ainsi que des recommandations pour des travaux ultérieurs.

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INTRODUCTION

The range of torpedoes is limited by the capacity of the energy source used to drive the motor or engine, and the speed of torpedoes is limited by the power developed by the motor, assuming that the battery or fuel supply can deliver the energy required at a fast enough rate. Thus, if a battery of the same weight as is used in the MK 37 torpedo, for example, could be produced, but possessing a larger ampere-hour capacity, then the range would be correspondingly increased. On the other hand, if the power output of the motor could be increased without an accompanying weight penalty, then the speed could be increased, but at the expense of range, unless a battery of larger capacity were also employed.

It should be possible to obtain the best of both of these situations by improving the battery and the motor at the same time. The indications are that this improvement is possible if the conventional electric motor in the MK 37 torpedo were replaced by a superconducting motor and if the Ag-Zn battery were replaced by a lithium-seawater battery. This combination of high-energy-density battery and high-power motor could improve torpedo performance markedly. (It is understood that redesign of the torpedo and of its launcher would be necessary to accommodate these changes and modification of the guidance system would be required to account for changes in the operating parameters. The justification for these improvements has yet to be established).

SUPERCONDUCTING MOTORS

There is great interest in superconductivity and machinery with superconducting windings because the materials used possess zero electrical resistance below some critical temperature. The attractions of using a zero resistance conductor are obvious, however, the drawback is the necessary low operating temperature. This temperature depends upon the superconductor used and is in the range of 4-18 K. Cooling by liquid helium (BP 4.2 K) is thus necessary with the added complexities of refrigeration, insulation, vacuum jackets, etc. In the case of air-launched torpedoes, the motor system

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would probably be pre-cooled on the ground prior to take-off and would be kept cool by the flow, through an umbilical cord, of liquid helium stored in a reservoir on the plane. Before torpedoes with superconducting motors could be air-dropped, however, the effects of shock and vibration on materials at cryogenic temperature would have to be investigated and any problems resolved. Superconducting windings would have to be adequately protected from shock since they may revert to the normal (resistive) state if subjected to shock energy above a maximum level. Ship-or submarine-launched torpedoes would likely be cooled by an on-board, closed-cycle helium liquefier/refrigerator. These devices can now be made relatively compact and more reliable than older machines and a single unit, when conveniently located, could service any number of torpedoes in their launchers.

Despite these complexities, superconducting motors, above a minimum power size, present real weight advantages. Compared to conventional electric motors, superconducting motors have the advantage of higher torque, higher efficiency and lower weight for a given power rating. Conversely, weight-for-weight, superconducting motors are 6-8 times more powerful than conventional electric motors (1). The reason is that superconducting windings can support high currents without the need for iron. The usual iron stator can, therefore, be dispensed with and there is more space for a larger field winding. In addition, the I^2R losses in such motors are very low since the winding resistance is negligible.

Superconducting motors can also be designed to operate at slow speed and could be directly connected to the propellers, thus obviating the need for a speed-reducing gear box and its attendant power losses, weight, vibration and mechanical noise. In small torpedoes with insufficient room for a motor with counter-rotating armatures, a one-to-one direction-changing gearbox would still be needed to drive both propellers from the single armature, but the low rotational speed would result in less noise than with the conventional speed-reducing gearbox.

One other property of superconducting windings, and this is due to their zero resistance, is that the circulating current can be made to be persistent by shorting the terminals of the winding when it achieves operating temperature. This is the usual mode of operation of superconducting solenoids and is significant in this context in that the field winding could be fully energized before the torpedo was launched. Suitable provision for electrical connection to an external power supply and control would have to be made in the launcher in this case; however, a further advantage of this system is that all of the battery power would be available to drive the armature.

There are two basic types of superconducting motor with several possible configurations for each. The simplest design is the homopolar machine and is based upon the Faraday disc. The first commercial application of superconductivity to a rotating machine was of this type. It consists essentially of a solenoid in the form of an annulus surrounding a metal disc mounted on a shaft (Fig. 1). Current-carrying brushes contact the disc at the edge and centre. Since the magnetic field is perpendicular to the disc, there is no reaction on the winding from motor loading and a simple dewar arrangement can be constructed around the winding.

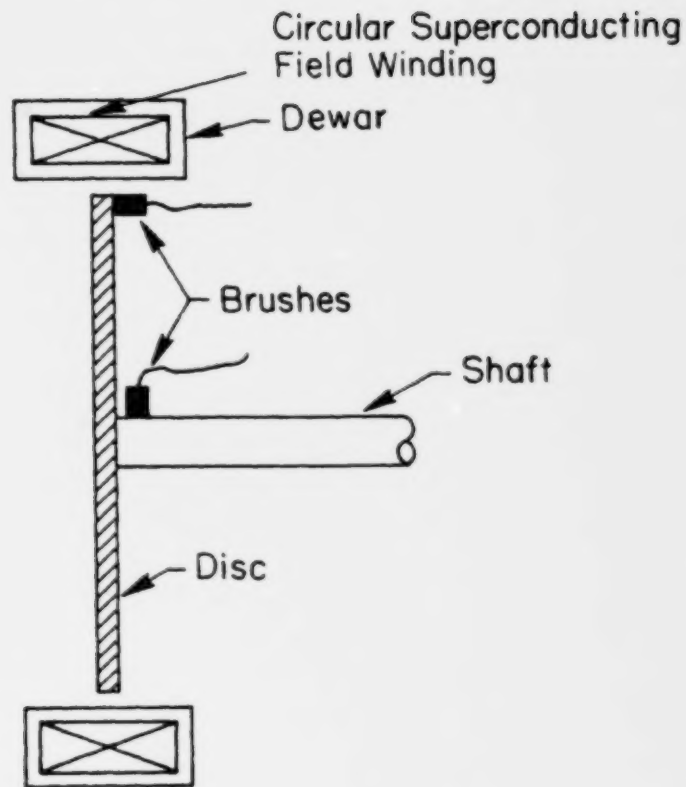


Fig. 1: Simplified cross-section of homopolar electric motor with superconducting field winding.

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The major disadvantage of this design is the inherent low voltage of the armature. This voltage is given by the expression (2)

$$V = \frac{\phi N}{60},$$

where ϕ is the useful flux in Webers and N is the speed in rpm. The useful flux is the fraction of the total flux intercepted by the disc between the inner and outer slip-rings or brush contacts and is simply

$$\phi = \pi (r_2^2 - r_1^2) B,$$

where B is the flux density in Teslas.

The voltage can be increased by segmenting the disc or by increasing its diameter which suggests that a flat, large diameter machine would have the preferred shape. For a motor small enough to fit in the MK 37, the armature voltage for a double slip-ring pair or drum configuration would be about 3 V ($B \sim 4$ T, $N \sim 1000$) and, for a 150 HP motor for example, the current would have to be in the tens of thousands of amperes. This high current, although possibly attainable from a high-energy-density battery, could not be supported by the brushes in a small homopolar motor. This type of superconducting motor is, therefore, not suitable for powering torpedoes.

The second basic type of superconducting motor is the common heteropolar machine with a wound, repulsion armature (Fig. 2). The field winding is superconducting and the rotor may or may not have superconducting coils depending upon the power requirements, cost, complexity and other considerations. Again the superconducting field provides a very high magnetic flux, but the full reaction of motor loading is now transmitted directly to the winding and it must be securely anchored to the frame. This need for increased support raises the refrigeration load markedly; however, more power can be developed in a smaller rotor of this type than in the homopolar machine.

A superconducting motor for torpedo propulsion would very likely have a conventional resistive armature, carbon brushes with a high metal content and a superconducting field winding. Some of the original superconductors would become suddenly normal when subjected to a changing magnetic field, but type II superconductors when operated within their ratings can tolerate the varying flux from armature rotation without losing their superconducting properties. The conductors most frequently used are alloys or compounds of niobium and titanium or tin in the form of micron-size filaments in a copper matrix; Nb_3Sn is often vapour deposited onto thin ribbons of stainless steel (3). The actual composition and configuration employed depend upon the application.

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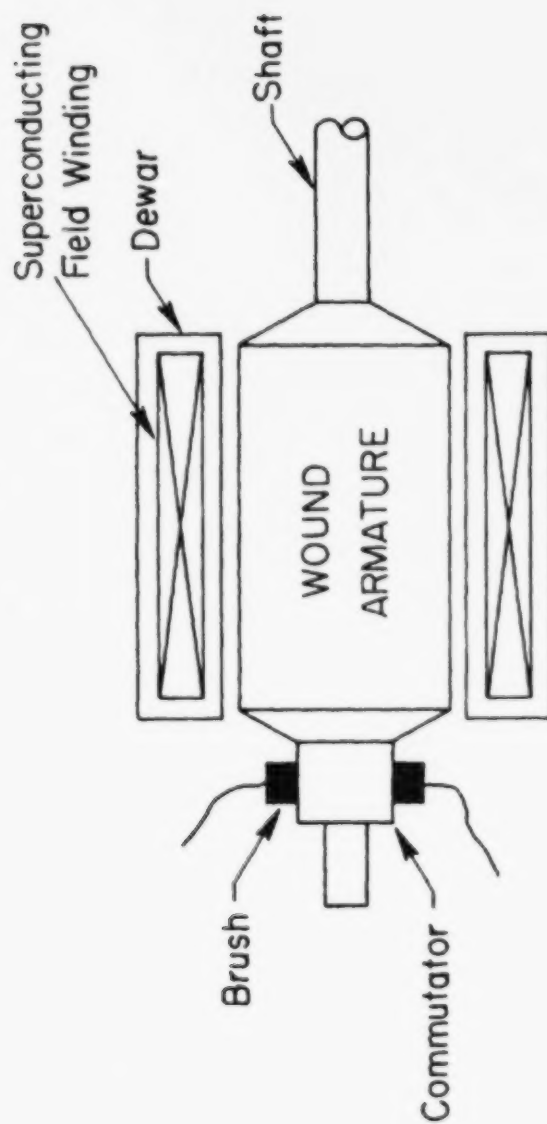


Fig. 2: Simplified cross-section of heteropolar electric motor with superconducting field windings.

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The field which may be obtained from an air-core winding may be calculated approximately from the expression for a solenoid. At the end of the coil (4,5)

$$H = \frac{4\pi}{10} \cdot \frac{NI}{2L},$$

where N/L is the number of turns per cm and I is the current. In general terms, NI/L may be replaced by the product of the thickness, S , of the coil and the current density, j , yielding

$$H = \frac{4\pi j S}{5}.$$

With a current density of $30,000 \text{ Acm}^{-2}$ (6) in a coil 2 cm thick it is possible to obtain a field of about 40 kOe which is four times higher than the field obtainable from a normal winding of the same size (7). Although iron is not needed in the magnetic circuit to achieve this high field, some external shielding would be required to reduce the stray field. Compensating windings could possibly be used, but they are probably impractical in a motor of this relatively small size. The external iron would also help to focus the flux lines and increase the interacting field somewhat but at the expense of added weight.

The use of a conventional resistive armature would allow more realistic terminal voltages than with the homopolar machine. The values would likely be in the 30-300 V range and the current requirements would be correspondingly reduced. Power losses in the brushes and in resistive connections would also be lower.

If a 150 HP superconducting motor were installed in the existing MK 37 torpedo, its speed would be increased by about 50% without enlarging the engine compartment. However, the advantage of using superconducting motors is not fully realized at this horsepower rating; maximum benefits begin to appear at ≥ 500 HP. A 500 HP heteropolar superconducting motor would not be much larger than one of 150 HP and its use in the MK 37 would result in a speed increase of about 100%, although the greater electrical power required (375 kW) would necessitate the use of a larger, more efficient battery.

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LITHIUM-SEAWATER BATTERIES

In electric motor-powered torpedoes, the limitations of size and weight necessitate the use of a high-energy-density battery. The Mg-AgCl battery used in some torpedoes employs seawater as the electrolyte and has an energy density of 26-40 Wh/lb depending upon the configuration. In the MK 37 torpedo, the Zn-AgO battery used develops ~ 80 V at 450 A and has an energy density of about 35 Wh/lb. The figure for the lithium-seawater battery is 3-4 times higher and the energy per unit volume can be four times greater depending upon battery size. In addition, the cost/kW is much lower since no silver is used and lithium is in abundant supply. This battery is an excellent candidate for use in torpedoes.

The overall chemical reaction of the lithium-water cell is



The hydrogen is evolved at a nickel or iron cathode. The theoretical energy density is 3830 Wh/lb of lithium and practical systems can develop ~ 1500 Wh/lb of reactants in a marine environment, where the weight of water consumed is not included. The need for a heat exchanger, circulation pump and associated plumbing reduces this figure by a factor of ten when the entire system is considered. Littauer and Redlien (8) have described the operation, manufacture and use of this cell in marine applications.

An example of the capabilities of the Li-water battery has been reported by Halberstadt et al. (9). A cylindrical battery weighing 946 lb and measuring 20 inches in diameter and 72 inches long had a capacity of 1200 Ah at 80 V. Compared to the Ag-Zn battery of the MK 37 torpedo, this lithium battery had 12 times the output but only 4 times the weight and 3 times the volume. If installed in a torpedo, it would be able to power a 120 HP motor for 1 hour, assuming that the superconducting field winding was in the persistent mode and armature losses were 5% (low bearing and windage losses because of low speed and independently-energized field). Higher power applications would not result in a proportionate increase in battery size and weight as the plumbing need only be upgraded, not repeated and the required increase in electrode area would mainly involve lightweight lithium.

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CONCLUSION

It has been shown that it is possible to increase the speed of the MK 37 torpedo by a factor of two or more by the use of a superconducting motor powered by a lithium-water battery. Lower noise and vibration are additional benefits. The combination might be considered as an alternative propulsion system in other torpedoes if high-speed turbines plus speed-reducing gearbox are considered too noisy.

RECOMMENDATIONS

It has not been possible to present specific information on torpedo-size superconducting motors as the required development work has either not been done or has not been published. The same situation exists in the case of suitable, compact, high-power lithium-water batteries, although it appears that such systems are not far from reality.

It is recommended that

1. A survey be conducted of the state-of-the-art of small superconducting motors;
2. a contract be awarded for the development of a superconducting motor suitable for use in a torpedo, if it is discovered in the survey that no such motors have already been developed;
3. a survey be conducted to determine the state-of-the-art of compact, high-power lithium-seawater batteries;
4. a contract be awarded for the development of a lithium-water battery suitable for powering a superconducting motor in a torpedo if no such battery already exists.

The recommendation for the awarding of development contracts is made in anticipation of the expected future use of superconducting motors in torpedoes.

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